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Performances of Neural Networks and LDPC Decoders for OFDM High Speed Transmission in Optical Fiber

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Abstract— ***This paper presents a comparison of the performances of coded OFDM (Orthogonal Frequency Division Multiplexing) for optical broadband transmission using Random Neural Network (RNN), a variant of RNN, Soft Decision Decoding (SDD) and LDPC channel decoding techniques. The performance evaluation is based firstly on the Error Vector Magnitude (EVM) to assess the effects of imperfections in the optical channel, and secondly on the estimated Bit Error Rate (BER) based on OSNR. The simulations are performed at a rate of 10Gb/s over 1000 km using VPI software cosimulation environment. The results show that the error correcting codes, particularly LDPC codes, are well suited and efficient for broadband.These codes provide satisfactory solutions for OFDM, reducing the effects of chromatic dispersion (CD), polarization mode dispersion (PMD), Intersymbol Interference(ISI) and non-linearities.***

Keywords—OFDM, BER, EVM, Optical fiber, Decoder, Neural network, SDD, LDPC, Broadband

I. Introduction

The transmission of high speed digital signals in telecommunication networks is of increasing interest with the discovery of OFDM multicarrier modulations. Coded OFDM (COFDM), are now used in many applications to maximize transmission rates. Commonly used transmission media are wireless channels [9]-[5] and optical fiber [8]-[12]-[10].

Our goal is to address OFDM in optical fibers because multicarrier modulations are not widely deployed in optical networks compared to wireless networks, taking into account the existence of specific channel imperfections such as the chromatic dispersion (CD), the polarization mode dispersion (PMD), non linearities and intersymbol interference (ISI) [2]. It is admitted that OFDM can be used for dispersion compensation [13]. The fact that the conventional modulations of transmission systems in optical fiber used so far in the majority are NRZ (no return to zero), RZ (return to zero), duo-binary and their variants. These kinds of modulation are quite simple and do not maximize the data rate because of their small spectral efficiency.

Meanwhile, neural network decoders are now studied as a different way to solve to overcome the complexity of the decoding process, allowing a simple hardware implementation of the receiver, compared to the existing iterative methods used in decoders.

In this context, we focused our study in a comparative approach of some coding techniques of OFDM over an optical fiber using Random Neural Network (RNN), a new implemented variant of RNN, Soft Decision Decoding (SDD) and LDPC channel error correcting codes. To achieve this goal, we designed a simulation platform of OFDM signal with a single mode fiber over 1000 km. We successively modulate subcarriers with QPSK, 4QAM, 16QAM and 64QAM modulations.

The Orthogonal Frequency Division Multiplex (OFDM) is a special case of Multicarrier modulations (MCM) wherein the subcarriers are orthogonal allowing multiple channels to be closer in order to reduce the use of bandwidth. A MCM signal can be modeled as follows:

$$S_{MCM}(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{N_{SC}} C_{ki} S_k(t - iT_S) \quad (1)$$

$$S_k(t) = \Pi(t) e^{j2\pi f_k t} \quad (2)$$

$$\Pi(t) = \begin{cases} 1, & (0 \prec t \leq t_S) \\ 0, & (t \leq 0, t \succ t_S) \end{cases} \quad (3)$$

with $S(t)$ the MCM signal, C_{ki} is the *i-th* information symbol of the *k-th* subcarrier, $S_k(t)$ is the waveform of the *k-th* subcarrier, N_{SC} is the number of carriers, f_k is the frequency of the *k-th* subcarrier, T_S is the symbol period, t_s is the observation period of the OFDM symbol, $\Pi(t)$ is the rectangular function.

Indeed we have:

$$\delta_{kl} = \frac{1}{T_S} \int_0^{T_S} S_k(t) S_l^*(t) dt = \exp\left(j\pi(f_k - f_l)T_S\right) \frac{\sin(\pi(f_k - f_l)T_S)}{\pi(f_k - f_l)T_S} \quad (4)$$

Let: $$f_k - f_l = m * \frac{1}{T_S} \quad (5)$$

with m a positive integer. This condition is the basic principle of OFDM which guarantees the use of orthogonal sub-carriers, allowing them to be closer channels in order to optimize the use of the spectrum. The resulting OFDM signal is in baseband time domain [11]:

$$S_{OFDM}(t)=\sum_{i=-\infty}^{+\infty}\sum_{k=-N_{SC}/2+1}^{k=N_{SC}/2}C_{ki}\Pi(t-iT_S)e^{j2\pi f_k(t-iT_S)} \quad (6)$$

$$S_k(t-iT_S)=\Pi(t-iT_S)e^{j2\pi f_k(t-iT_S)} \quad (7)$$

$$f_k=\frac{k-1}{t_S} \qquad \Pi(t)=\begin{cases}1, & (-\Delta_G \prec t \le t_S)\\ 0, & (t\le -\Delta_G, t\succ t_S)\end{cases} \quad (8)$$

where SB(t) is the OFDM signal, *ΔG* is the guard interval characterizing the cyclic prefix and *Π(t)* the rectangular function taking into account the guard interval.

The simulation platform of the optical transmission chain has been developed with the cosimulation softwares VPITransmissionMaker 9.0 from VPI Photonics GmbH [14] and MATLAB R2010a from MathWorks.

Performance tests of the transmission chain were carried out on the basis of the Error Vector Magnitude (EVM) and Bit Error Rate (BER). All these tests were performed according to the Optical Signal to Noise Ratio (OSNR).

II. Material and Methodology

A. The transmission channel model

The optical transmission channel, since we use a Single-Mode Fiber (SMF) can be modeled in the frequency domain taking into account the two polarizations as follows [11]:

$$H(t,f)=e^{j\Phi_D(f)}.T_k \quad (9)$$

$$\Phi_D(f)=\pi.c.D_t.f^2/f_{LD1}^2 \quad (10)$$

$$T_k=\prod_{l=1}^{N}\exp\left(\left(-\frac{1}{2}j.\vec{\beta}_l(t).f-\frac{1}{2}\vec{\alpha}(t)\right).\vec{\sigma}\right) \quad (11)$$

With *H(t,f)* the filter that models the optical fiber media, $\Phi_D(f)$ the phase dispersion due to the effect of chromatic dispersion in the fiber, T_k is the Jones matrix of the optical link representing the effect of the polarization dependence including PMD and PDL (Polarization dependent Loss), *N* is the number of cascaded elements, $\vec{\sigma}$ is the Pauli matrix vector, PMD and PDL represented by their birefringence vectors $\vec{\beta}_l$ and $\vec{\alpha}_l$.

In case of transmission over a single mode optical fiber, unique single mode propagation is permitted. If we consider the transmitted signals time variable, the E and E' resulting fields received at the remote end of the optical fiber can be described by:

$$E(t)=e^{j(\omega_{LD1}t+\phi_{LD1})}.S_B(t),\; E'(t)=e^{j(\omega_{LD1}t+\phi_{LD1})}.S_B(t)*h(t) \quad (12)$$

with ω_{LD1} and ϕ_{LD1} respectively frequency and phase angular of the transmitter laser. The symbol * represents the convolution product and *h(t)* is the impulse response of the optical fiber channel (SMF fiber).

The signal at the output of the optical receiver is:

$$r(t)=e^{j(\omega_{Off}t+\Delta\phi)}.r_0(t), \qquad r_0(t)=S_B(t)*h(t) \quad (13)$$

with $\omega_{Off}=\omega_{LD1}-\omega_{LD2}$ et $\Delta\phi=\phi_{LD1}-\phi_{LD2}$

B. Random neural network model

The Random Neural Network (RNN) is a neural network model inspired by the spiking behaviour of biophysical neurons [3]. A RNN is a recurrent neural network of *N* fully connected neurons which exchange positive and negative signals in the form of unit amplitude spikes.

At any time *t*, the state of neuron *i* is described by its signal potential $k_i(t)$ which is a non-negative integer associated with the accumulation of positive signals at the neuron. We say that neuron *i* is excited when $k_i(t) > 0$, else if $k_i(t) = 0$ then it is idle or quiescent. A closely related parameter is $q_i(t) = \Pr[k_i(t) > 0] \le 1$, which is the excitation probability of the neuron.

When neuron *i* is excited, it can randomly fire according to the exponential distribution with rate r_i resulting in the reduction of its potential by 1. The fired spike either reaches neuron *j* as a positive signal with probability $p^+(i;j)$ or as a negative signal with probability $p^-(i;j)$, or it departs from the network with probability *d(i)*. These probabilities must sum up to one, yielding:

$$\sum_{j=1}^{N}\left[p^+(i,j)+p^-(i,j)\right]+d(i)=1,\forall i \quad (14)$$

When neuron *i* is excited, it fires positive and negative signals to neuron *j* with rates:

$$w^+(i,j)=r_i p^+(i,j)\ge 0 \quad (15)$$

$$w^-(i,j)=r_i p^-(i,j)\ge 0 \quad (16)$$

C. Overall optical transmission chain

The digital optical transmission channel used is illustrated in Figure 1.

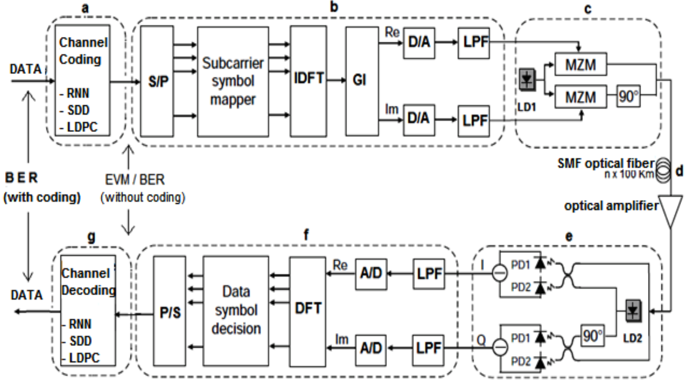


Figure 1. OFDM optical transmission channel: a- channel encoder; b- RF OFDM transmitter; c-RF/Optical converter, d- Optical SMFfiber; e- Optical/RF Converter; f- OFDM RF Receiver g-channel decoder.

OFDM optical transmission chain is simulated in VPITransmissionMaker 9.0 and Matlab cosimulation environments. Error-correcting codes are not available in VPITransmissionMaker. So cosimulation with Matlab is necessary because it allows one to add specific processing for channel coding.

The developed processing platform is a universe of interconnected modules where some new galaxies were created. The processing chain used is shown in Figure 2. The simulation model "OFDM for Long-Haul Transmission" available in VPITransmissionMaker was used as a model of inspiration. New galaxies LAME_Tx-OFDM and LAME_Rx-OFDM are the electrical OFDM transmitters and receivers modified from the reference galaxies Tx_El_OFDM and Rx_El_OFDM_BER.

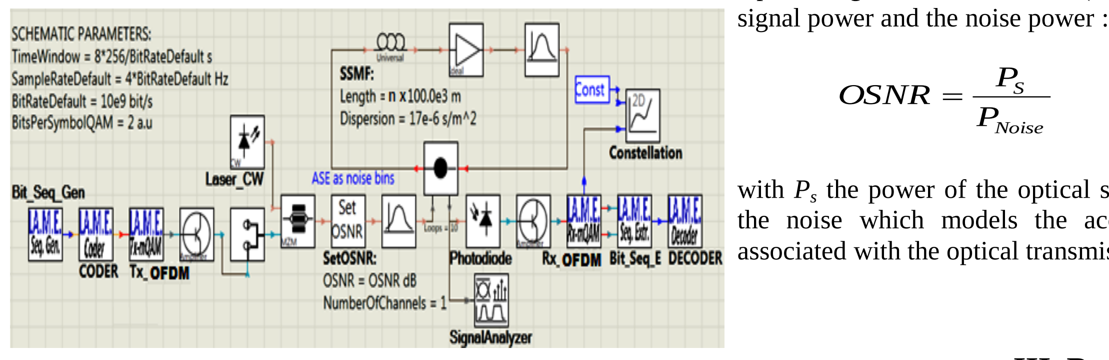


Figure 2. Scheme of the simulation in VPITransmissionMaker 9.0

We monitor the OSNR so as to fix its successive values at the transmitter side which can influence the calculation of BER, modeling the variable effect of imperfections in the optical transmission channel.

D. Estimation of the EVM, BER and OSNR

The EVM is a measure of the quality of the transmission through the quality of the demodulation.

EVM_{RMS} is the value of the root square (Root Mean Square) of the difference between the received symbols and ideals symbols, normalized. It is given by [7] :

$$EVM_{RMS} = \left[\frac{\frac{1}{N}\sum_{r=1}^{N}\left(\left(I_r - \bar{I}_r\right)^2 + \left(Q_r - \bar{Q}_r\right)^2\right)}{\frac{1}{N}\sum_{r=1}^{N}\left(I_r^2 + Q_r^2\right)} \right]^{1/2} \quad (27)$$

The calculation of EVM_{RMS} is performed before channel decoding.

The Bit Error Rate (BER) is the measuring parameter the best known of the quality of a digital transmission, and represents the ratio between the number of erroneous bits and the total number of bits transmitted. The determination of the BER is based on the following definition:

$$BER = \frac{Number_of_erroneous_Bits}{Number_of_Transmitted_Bits} = \frac{N_{err}}{N} \quad (28)$$

For a better estimation of BER, we used a Monte Carlo approach [6], which consists in a stochastic simulation with a large number of random symbols, to estimate the behavior of the system. Therefore, we can estimate that :

$$BER_{MC} = \lim_{N \to +\infty}\left(\frac{N_{err}}{N}\right) \quad (29)$$

BER calculation is performed before and after the channel decoding, according to the OSNR. The simulation is performed under the effect of the Chromatic Dispersion (CD) and the Optical Signal to Noise Ratio (OSNR), the ratio of the optical signal power and the noise power :

$$OSNR = \frac{P_S}{P_{Noise}} \quad (30)$$

with P_s the power of the optical signal, P_{Noise} the total power of the noise which models the accumulation of all the noises associated with the optical transmission chain.

III. Results

A. Error correcting codes techniques

Random Neural Networks (RNN) are straightforward adaptation of standard feed-forward neural networks to allow them to model sequential data. At each time step, the RNN receives an input, updates its state, and makes a prediction. The model presented is designed to decode the (7;4) Hamming code, a class of (n;k) single error correcting block codes [1] that has the property (n;k) = $(2^r\text{-}1;\ 2^r\text{-}1\text{-}r)$ where r is the number of parity bits.

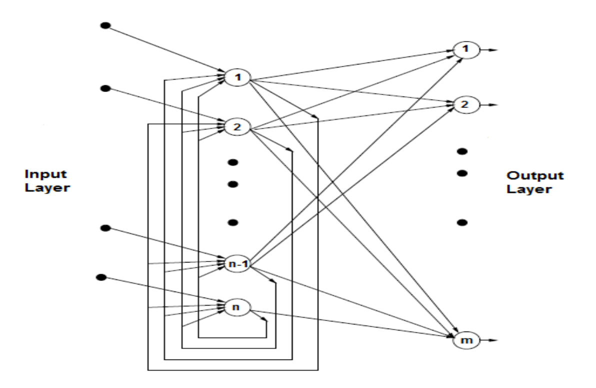


Figure 3. Architecture of a RNN

The RNN Decoder (RNN_ff) consists of two layers, the input layer, which has 7 neurons, is a fully inter-connected layer. This layer is connected to the output layer, which consists of 14 neurons, through feed-forward connections. The input layer accepts the bits of the received perturbed codeword at the end of the transmission channel and acts as an association layer which, through training, can extracts the relation between the different bits of each codeword and encodes this relation into a weight matrix. On the other hand, the output layer acts as a classification layer in which the index of the output neuron that produces the minimum value indicates the index of the decoded codeword.

We defined also a variant of the RNN Decoder (RNN_ff_New) in which the output layer has 4 neurons to let the neural network decoder implement completely the decoding process by outputting the decoded bit sequence of length k.

In Soft Decision Decoding (SDD), the decoding of block codes is carried out by seeking maximum correlation between the incoming corrupted codewords and the locally generated codewords. This method does not suggest making decisions in each bit, but only in codewords. It is complex to be implemented since the received vector is to be correlated with all possible codewords and then the vector yielding the highest correlation (closest codeword to the transmitted one) is selected. The SDD decoder implemented is based on the (7;4) Hamming code.

LDPC codes (Low Density Parity Check) created by Gallager in 1960, are linear block codes for which the parity check matrix has a low density of “1” bit [4]. The method of iterative decoding of LDPC codes requires long blocks of message and it is based on the LLR (Log-Likelihood Ratio).

Table 1 summarizes the characteristics of the decoders used in the transmission chain.

DECODERS	PARAMETERS		
	k	n	r (= n-k)
LDPC	32400	64800	32400
SDD	4	7	3
RNN_ff	4	7	3
RNN_ff_New	4	7	3

Table 1: Decoders parameters: k = length of the block of the message in bits, n = length of the code word, r = number of redundancy bits

The simulations helped us to plot the evolution curves of EVM as a function of OSNR. Similarly, the estimations of evolution of the BER curves before and after channel decoding were performed according to the OSNR.

B. EVM as a function of OSNR

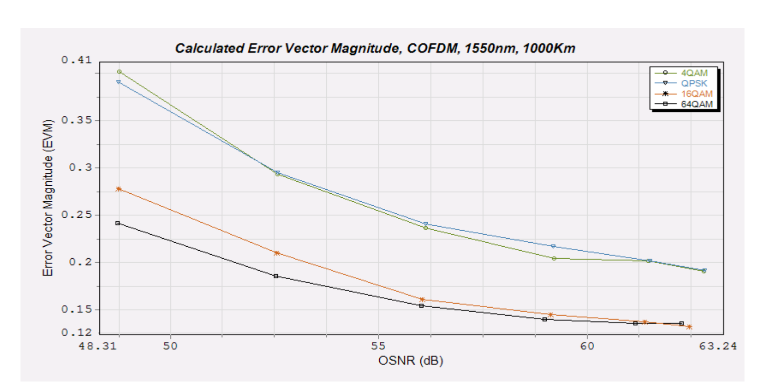


Figure 4. Error Vector Magnitude of the modulations QPSK, 4QAM, 16QAM and 64QAM based on OSNR

The results of EVM measurements are shown in Figure 4, they reflect good values of EVM, characterizing proper transmission of signals, and are improved with the increase in OSNR. In addition there is also an improvement in EVM with the increased of modulation level because symbols at the receiver side are more closed to ideal points when we move from 4QAM modulation to 64QAM modulation.

C. BER as a function of OSNR for different modulations and error correcting codes

The results allow comparing the Bit error rate (BER) of the COFDM transmission chain according to the channel encoding used. The curve plot is made based on the OSNR.

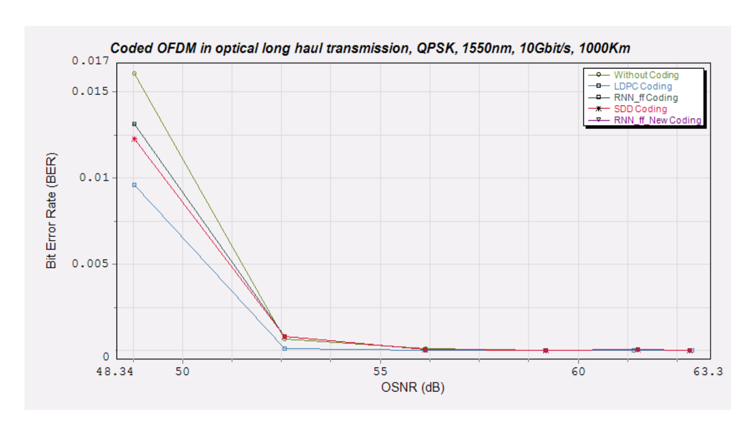


Figure 5. BER of error correcting codes with QPSK modulation

The Figure 5 and following figures show the simulation results for QPSK, 4QAM and 16QAM modulations respectively. The simulation reflects the effectiveness of error correcting codes, and in particular the LDPC code whose bit error rates are closer to zero.

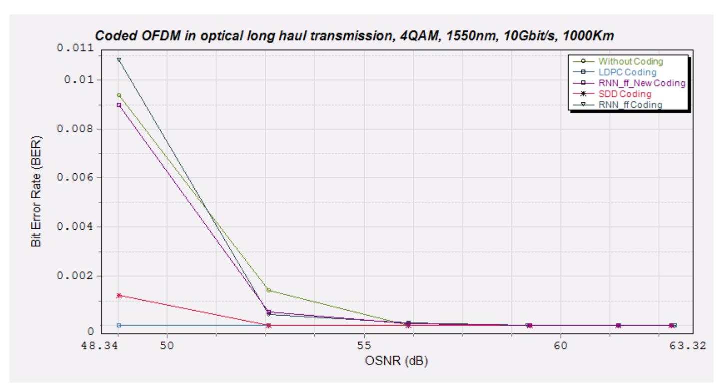


Figure 6. BER of error correcting codes with 4QAM modulation

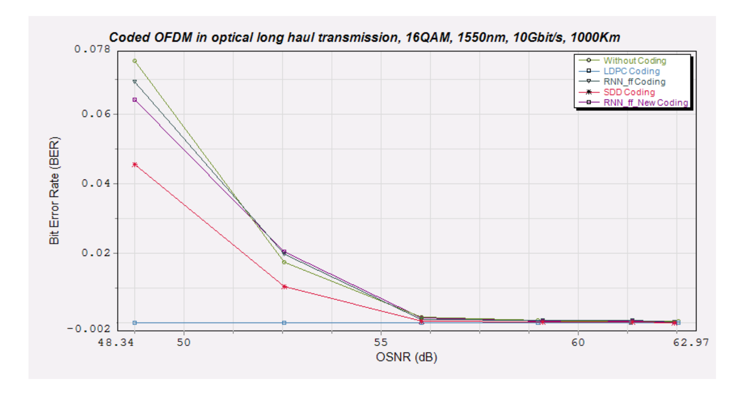


Figure 7. BER of error correcting codes with 16QAM modulation

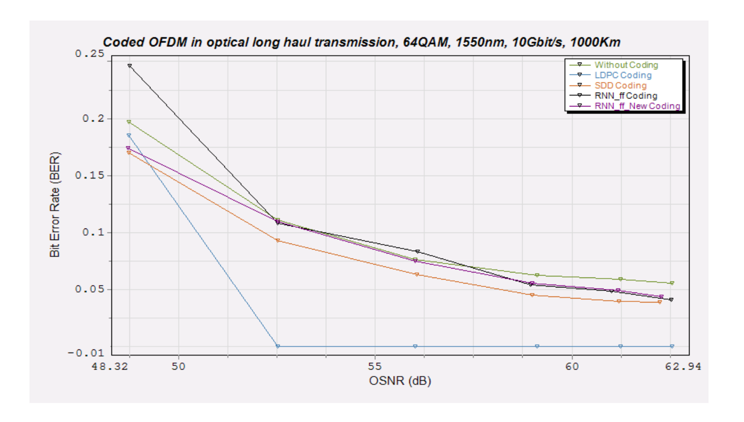


Figure 8. BER of error correcting codes with 64QAM modulation

The curve of the transmission of 64QAM in Figure 8 shows weak decoding techniques for RNN decoders. However LDPC decoder presents a good BER closer to zero for OSNR values higher than 52.5dB. This also shows that the effectiveness of error correcting codes strongly depends on the modulation level selected.

IV. Conclusion

The results show that the error-correcting codes used, particularly LDPC codes, are well suited and efficient for broadband. These codes provide satisfactory solutions for OFDM in optical fibers, because they allow one to reduce the effects of chromatic dispersion (CD), polarization mode dispersion (PMD), Intersymbol Interference(ISI) and non-linearities.

Furthermore, the simulations show also the superiority of the LDPC codes than other coding techniques and thereby provide a view of the LDPC codes as ideal solution of channel coding suitable for optical transmission channels.

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